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Transient Emissions from Radio-Active Stars: Implications for Wide-field Radio Surveys

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Variability is a common characteristic of magnetically active stars. Flaring variability is usually interpreted as the observable consequence of transient magnetic reconnection processes happening in the stellar outer atmosphere. Stellar flares have been observed now across 11 decades in wavelength/frequency/energy; such a large span implies that a range of physical processes takes place during such events. Despite the fact that stellar radio flares have long been recognized and studied, key unanswered questions remain. I will highlight what, in my opinion, are some of these questions. I will also describe recent results on stellar flare emissions at radio wavelengths, discussing the nature of coherent and incoherent emissions and the prospects of wide-field radio imaging telescopes for studying such events.

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1. Which Stars Flare?

At first glance, a comparison of some of the titles from the early days of radio astronomy with some of the targets being talked about here suggest that not much has changed: witness Lovell (1963) "Radio Emission from Flare Stars" and Bastian et al. (1990) with the same title. Indeed, Sections 3 and 4 of this article describe radio emission from flare stars (among other classes of stars). While some of the "usual suspects" remain favorite targets for radio observations due to their interesting nature, the advent of sensitive radio interferometers has increased our knowledge of radio emission and it is now recognized that radio emission can be produced in the atmospheres of many different types of stars. In particular, as described in Güdel (2002), it is now known that stellar radio emission occurs across the HR diagram, with a variety of manifestations. Those objects in the "cool half" of the HR diagram, lying roughly near the main sequence and with spectral types F and later, display predominantly nonthermal emission. This nonthermal emission is intimately connected with the presence of magnetic fields whose dynamical re-arrangement during magnetic reconnection processes can lead to transient increases in associated emissions. Thus, these cool stellar objects displaying nonthermal emission are all potential "flare stars"; the classic moniker must be expanded from the usual connotation of dMe flare stars to include all stars with evidence for large-scale surface magnetic fields. Radio flares of one kind or another have been seen in almost all kinds of cool stars displaying other signatures of magnetic activity.

2. Expectations from the Sun

The Sun is the source of a rich variety of radio emissions which can be traced to thermal or nonthermal emissions. Flaring variability is confined to strong magnetic field regions. Even though the Sun is well-studied at radio wavelengths, key questions remain. One illustration of where further investigation has revealed new insights into radio flare processes is examining the use of the assumption of isotropic pitch-angle distribution in gyrosynchrotron emission. Employing temporal and spectral observations of impulsive solar radio flares at GHz frequencies, Lee & Gary (2000) have been able to infer some of the properties of electrons injected into magnetic traps, finding that an initially narrow distribution of electron pitch angles is required. In stellar radio observations, one of the standard assumptions is that of an isotropic pitch angle distribution; this paper, along with work on other aspects of gyrosynchrotron emission from solar radio flares reveals the Pandora's box opened by high quality flare observations, and highlights some areas in stellar radio flare studies where the next generation of radio facilities can make progress.

One of the key advances solar radiophysics made in the 1950s which allowed identification of the mechanisms involved in metric and decimetric solar radio emissions was the use of the dynamic spectrum. Wild et al. (1959), in particular, showed that the complex drifting structures present in the frequency-time domain could be interpreted as the intrinsic drift of beams of electrons travelling through the upper solar atmosphere, generating plasma radiation at the ambient electron density. Such dynamic spectral analyses have been used to identify the likely location of particle acceleration in the solar corona (Aschwanden & Benz 1997). Under the assumption that the observed emission is plasma radiation at the fundamental or harmonic, produced by a beam of electrons travelling through the solar atmosphere and generating Langmuir waves at the local electron density, the observed frequency drift can be related to atmospheric properties and intrinsic

motion via:

$$\frac{d\nu}{dt} = \frac{\partial \nu}{\partial n_e}\frac{\partial n_e}{\partial h}\frac{\partial h}{\partial s}\frac{\partial s}{\partial t} \tag{2.1}$$

where ν is the observed frequency at time t, n_e is the electron density, h is the radial height in the atmosphere and s is the path length travelled in the atmosphere. This equation can be simplified under the assumption of a barometric atmosphere, to $\dot{\nu} = \nu \cos\theta v_B/(2H_n)$, where v_B is the speed of the exciter whose motion causes the plasma radiation. Speeds from 0.1–0.5c have been inferred using such analyses (Wild et al. 1959). The miriad other kinds of solar radio bursts, particularly at low frequencies, testifies to the complexity of solar radio emissions. I have highlighted here two examples, which are illustrative of the kinds of observations stellar radio astronomers can use to study similar processes in stellar environments.

Should we expect radio emission from the most active stars to behave like the Sun? Intense radio emission is found to be correlated over ten orders of magnitude with X-ray emission in a sample which includes active stars and individual solar flares (Benz & Güdel 1994). The correlation points out the necessity for strong magnetic fields to both accelerate electrons and heat plasma, and that the basic phenomenology must hold despite physically different length scales, gravities, and interior conditions found in these vastly different stars (T Tauri stars, coronal giant stars, active binary systems, dMe flare stars) compared with the Sun. The Sun's corona is well-described by relatively cool high temperature plasma, with $T_{cor} \sim 2\times10^6$K, with electron acceleration localized in space and time, appearing in regions associated with large magnetic field strengths, and only transiently. In contrast, most active stars have a distribution of coronal plasma which peaks at hotter temperates, generally 8–10 $\times10^6$K (Güdel 2004) and extending up to 40×10^6K in periods of quiescence. Electron acceleration, as diagnosed by nonthermal radio emission, appears to be persistent (Chiuderi Drago & Franciosini 1993) and taking place on a global scale (Franciosini & Chiuderi Drago 1995), in addition to transient acceleration episodes identified as flares. Even if the same basic phenomena are at work (magnetic heating of coronal loops, etc.) it is clear these atmospheres will have different effects on free-free and gyroresonant opacities ($\kappa_{gr} \sim T^{s-1}$, $\kappa_{ff} \sim T^{-3/2}$), and that the hotter coronae favor escape of plasma radiation (White & Franciosini 1995).

3. Incoherent Radio Flares

The most common kind of stellar radio flare is characterized by transient increases in flux density on timescales of tens of minutes up to days or longer, and is associated with low degrees of circular polarization. The flare temporal evolution is similar at adjacent frequency bands, pointing to optical depth effects in modifying the emergent radiation. Such flares can be associated with X-ray flares (see Güdel et al. 1996, Osten et al. 2004) although the assocation is not 100% (see discussion in Smith et al. 2005, Osten et al. 2004). These incoherent radio flares are generally attributed to gyrosynchrotron emission from mildly relativistic electrons (Dulk 1985).Due to sensitivity constraints, most radio stellar flare observations have taken place at GHz frequencies. Multi-frequency observations have illuminated some of these key points. The emission outside of the flare can attain a moderate amount of circular polarization. A simple model in which there is a constant level of flux and circular polarization (corresponding to quiescence) plus a varying amount of flux which is intrinsically unpolarized can fit the temporal variability of circular polar-

ization during some large-scale flares in which an inverse relationship between flux and circular polarization is noted (Osten et al. 2004 and Figure 1, left). During the rising phase of the flare the spectral index increases, becoming large and positive, (Osten et al. 2004, 2005 and Figure 1); with spectral index defined so that $S_\nu \propto \nu^\alpha$, this can be interpreted as optically thick conditions in the flare rise with a decrease back to optically thin conditions as the flare progresses.

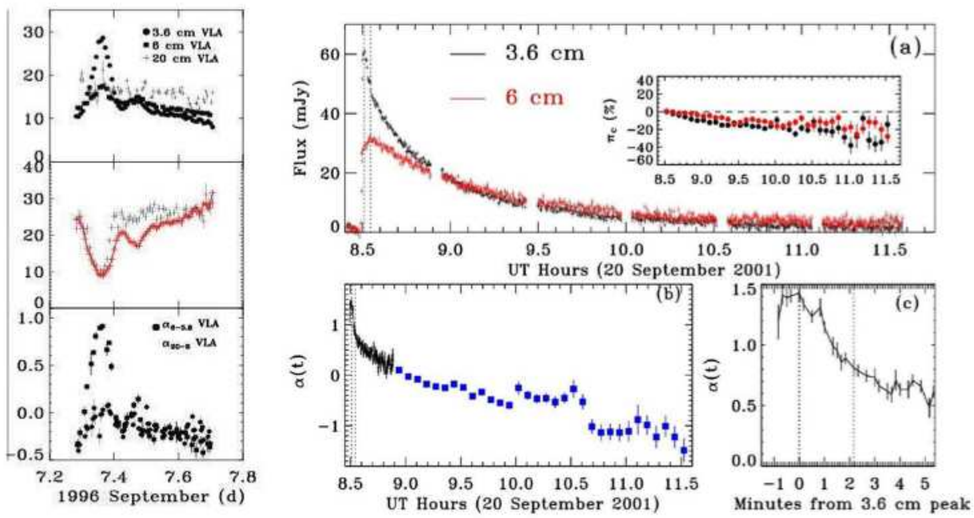

Figure 1: (left) Multi-frequency radio flare on the active binary system HR 1099 (V711 Tau) which illustrates the circular polarization and spectral index trends discussed in the text. Top panel displays flux variation in mJy at three frequencies; middle panel displays temporal trend of observed percent circular polarization (plusses) with a model for the transient increase in flux density being unpolarized; bottom panel displays temporal trend of spectral index; the positive correlation with flux density suggests optical depth effects occurring during the flare. Taken from Osten et al. (2004). **(right)** Spectral index and circular polarization variations during a large flare outburst observed on the dMe flare star EV Lacertae (Osten et al. 2005). At flare peak there is no measurable polarization, and the spectral index changes in the first minutes of the flare point to complex and fast dynamical changes in the flaring plasma.

The largest stellar radio flares at cm wavelengths illustrate some extreme properties: peak radio luminosities exceeding 100× the quiescent radio luminosities, lasting for tens of days, and with recurrence timescales on the order of several times per year (Richards et al. 2003).Daily monitoring of several active stars, which revealed the frequency of these events, has occurred primarily at cm wavelengths, and the sparse data collection allows only cursory examination of the flaring process which can produce these events. Pointed observations only rarely pick up these events; VLA and VLBA observations from a serendipitously detected superflare (Beasley & Bastian 1998) showed that the peak frequency exceed 20 GHz on 5 of the 7 consecutive days during which the flare was observed. Based on expectations from solar flares, the accelerated electrons producing the nonthermal radio emission should also produce nonthermal hard X-ray emission, but until recently there had not been a confident claim of detection of such emission, despite the reportings of large X-ray flares. A serendipitously detected stellar X-ray superflare from the nearby active binary II Peg with the Swift satellite (Osten et al. 2007) displayed the first evidence for nonthermal hard

X-ray emission, with detections out to 200 keV. This allowed the electron density distribution to be investigated in a stellar flare for the first time. An estimation of the flare energetics revealed rough agreement between nonthermal and thermal energy estimates, with evidence for continued heating (and particle acceleration) in the decay phase of the flare. This was only one flare, and it lacked multi-wavelength coordination; future attempts to obtain X-ray and radio coverage of such events are the stellar astronomers' best hope for making significant advances in the area of stellar flare particle acceleration.

Key unanswered questions in incoherent stellar radio flares:

1. Can detailed spectral and temporal observations of stellar radio flares across a large frequency range be used to determine the evolution of particle acceleration and investigate particle injection? Observations which are clearly in the optically thin regime are needed to deconvolve spectral index evolution into optical depth evolution (which involves changing magnetic fields and particle distribution) and evolution of the particle distribution.

2. Is there evidence for particle trapping or pitch-angle dependence of emission from stellar radio flares? By having detailed spectral and temporal observations, particularly in the optically thin regime, such effects can be investigated.

3. How does the nonthermal energy release compare to the rest of the flare energy budget? Answering this question allows investigations into the flare process itself, the partition of flare energetics, and the timing of particle acceleration and plasma heating.

4. How do these things compare to relatively well-studied solar flares, and how do they vary in different stellar environments? Does a flare on a diskless T Tauri star behave the same way as that on a dMe flare star, or a coronal giant star? Observations can be used to infer the physical conditions present in the atmospheres of flaring stars, which can be important for other reasons (e.g. physical conditions around young stars).

In order to answer these questions, a combination of broad-band coverage and sensitivity is needed, particularly at high frequency. In addition, in order to study the stellar "superflares", the ability to respond quickly to external triggers (e.g. from X-ray telescopes) is needed.

4. Coherent Radio Flares

A key point about stellar radio flares is that they come in (at least) two flavors: the largely unpolarized flares described above, and then another category, described by high degrees of circular polarization (reaching 100%, something not found in other astrophysical sources of radiation), with timescales varying from milliseconds up to hours, emission structured in both frequency and time and no clear association with X-ray flares. These properties constrain the intrinsic brightness temperatures to be in excess of the 10^{12}K limit for incoherent radiation set by inverse Compton scattering and thus must be coherent in nature. Study of other classes of active stars have revealed evidence for similar kinds of transient coherent emission. The frequencies at which such emission has been detected range from metric wavelengths (Kundu & Shevgaonkar 1988) to centimeter wavelengths (Bingham et al. 2001). Coherent bursts appear structured in time and frequency. This was noted in previous observations of flares from the classic flare stars (Bastian et al. 1990), although the ability to study such events in detail had been limited by a combination of bandwidth coverage and time resolution. Güdel et al. (1989) used three single-dish telescopes to determine that the radio bursts often observed on AD Leo were in fact extraterrestrial and covered a large

frequency range, but quantitative analysis of burst properties was elusive. On the Sun there are two distinct coherent emission mechanisms at work: one being associated with plasma radiation (operating at the fundamental or harmonics of the plasma frequency) and the other associated with an electron cyclotron maser (operating at the fundamental or harmonic of the electron cyclotron frequency). The quandary with radio bursts seen on flare stars lay in not being able to prefer one mechanism to the other, based on the available observational discriminants, usually consisting of lower limits to brightness temperature, and observed degrees of circular polarization.

The advent of wide bandwidth radio instruments has revolutionized the arena of coherent stellar radio bursts. By combining large frequency bandwidth ratios with high time resolution, instrumental backends originally designed for use in studying pulsars can be harnessed to a quantitative study of stellar radio burst characteristics. In a study by Osten & Bastian (2006), timescales, instantaneous bandwidths, and frequency drifts of a number of bursts could be measured, along with flux densities and circular polarizations. The observed properties of the bursts, in concert with ancillary knowledge about the stellar atmospheric properties, led the authors to prefer the plasma radiation mechanism.

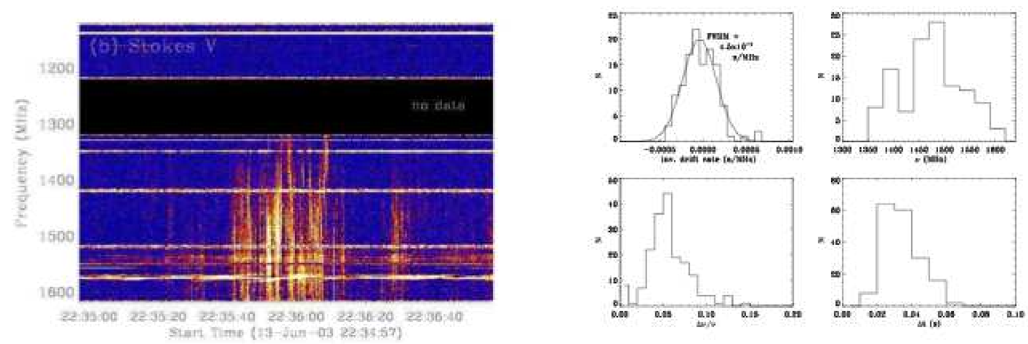

Figure 2: (left) Dynamic spectrum of stellar radio burst observed with Arecibo on the flare star AD Leo (Osten & Bastian 2006). The burst illustrates several key points about stellar coherent flare emission: large amounts of circular polarization (here $>$ 90%); evidence for structure in the frequency and time domains. The time resolution here of 10 ms allowed lower limits on brightness temperature of 10^{14}K. **(right)** Histograms of burst properties deduced from analysis of the dynamic spectrum. Important burst properties that could be constrained using such observations include the drift rate of the bursts, instantaneous bandwidth ratio, time duration, and start frequency. Based on these properties, Osten & Bastian concluded that the bursts were likely produced by plasma radiation, and were the stellar equivalent of decimetric solar type III bursts.

Further observations with even higher time resolution (Osten & Bastian 2007) have revealed additional behaviors. The appearance of drifting structures in the dynamic spectrum is apparently common, but complex diffuse structures have also been seen. These highest time resolution observations of stellar radio bursts indicate burst timescales of several ms, indicating a lower limit to the brightness temperature of 10^{18}K. This places severe constraints on the emission process in this instance; based on the observed properties of the drifting structures seen here in comparison with those seen in earlier observations, a cyclotron maser emission may be preferred. Osten & Bastian ruled out other causes of the dynamic spectral structure, such as that induced by stellar atmospheric

properties, or scattering in the stellar corona or intervening interstellar medium.

Currently only the largest flares are amenable to such high time-resolution, wide bandwidth dynamic spectral analysis, but coherent flares are detected across a range of radio luminosities and from almost all classes of magnetically active stars. *Coherent emission is a manifestation of magnetic activity which has hitherto been unexploited for what it can reveal about stellar atmospheric properties.* New generations of radio telescopes will probe the low frequency regime, where coherent emissions are expected to be richer and more varied. Although I have concentrated primarily on flare stars in this brief discussion, recent work in other areas has shown the importance of coherent processes in producing stellar radio emission – the pulstar of Kellett et al. (2007),and the highly circularly polarized rotationally modulated emission from some very low mass stars and brown dwarfs (Hallinan et al. 2007).

Key unanswered questions in coherent stellar flares:

1. What is the nature of coherent emission in different stellar systems? The observational manifestation is large amounts of circular polarization which are transient on some timescale. As has been noted in previous papers on this subject (Bastian et al. 1990), there is an ambiguity as to whether such emissions could be produced by a plasma emission process or a cyclotron maser process. Based on consideration of both the stellar atmospheric properties, often largely unknown, and more detailed observational constraints on the coherent stellar radio bursts, it may be possible to determine whether particular types of coherent processes preferentially operate in particular stellar environments.

2. What is the relation of coherent flaring to flaring in other wavelength regions? Coherent emission generally involves energetic particles, and solar studies have shown correlations between nonthermal X-ray flare signatures and electron beam-excited radio emissions (Aschwanden & Benz 1997). Previous studies on stellar flares have tended to find no clear association between coherent flares and flare signatures at other wavelengths (Kundu et al. 1988). Determining whether an association exists will be enormously helpful in clarifying some of the processes involved in stellar flares.

3. What do analyses of flare structure in the frequency and time domains imply about constraints on stellar atmospheric (particularly B, n_e) structuring? The ability of dynamic spectral analyses to reveal crucial information about the densities and magnetic field strengths at various points in the atmosphere in which radio emission from sub-bursts is produced allows a probe of the physical conditions in stellar atmospheres which cannot be done using techniques at other wavelength regions, where often the disk-averaged emission and density-squared dependence of the thermal emission introduce biases. This can be especially important in areas such as using coherent radio emission from T Tauri stars to probe the star-disk connection.

5. Implications for Wide-Field Imaging

It is curious, given the large flux densities recorded in large stellar outburst from pointed radio observations, that unbiased radio surveys apparently don't find many radio stars. As an example, the FIRST survey (Helfand et al. 1999) surveyed 5000 square degrees down to a 0.7 mJy limit at 20 cm and found 26 stellar radio sources, with only 16 of those being new detections. Some of the limiting factors to survey sensitivity for transient emission include area coverage, sensitivity, and time on field, all of which increase the likelihood of catching transient behavior. Based on

the known properties of nearby radio-active stars, we can inform some expectations for wide-field imaging that the next generation of radio telescopes (e.g. ATA, LOFAR, MWA, LWA) can expect to see. I concentrate here on M dwarf flare stars and active binary systems due to the fact that more is known about their behavior.

M dwarf flare stars can have large coherent bursts, up to 500 times the quiescent flux density levels, reaching Jy-level flux densities for the nearest studied objects. These events have been observed at decimeter and meter wavelengths. Telescopes with sub-mJy sensitivity will be able to catch similar events from dMe flare stars at distances up to $\approx$ 150 pc. These high intensity events are relatively rare, however, with duty cycles $<$ 1%. Incoherent bursts tend to be smaller in amplitude. 40% of surveyed flare stars were detected at 20 and 3.6 cm (White et al. 1989). If they all behave the same way this is a large reservoir of stellar transient radio sources which, given the enhancements, can be seen out to large galactic distances. An order of magnitude estimate of the number of flare stars visible with telescopes of sub-mJy sensitivity can be made by computing $n4\pi d^3/3 f_R$, where n is the space density of flare stars (0.08 stars per pc^3, Reid et al. 2007), d is the maximum distance to which telescopes are sensitive using the general numbers above, and f_R the fraction of radio-emitting objects. Given the parameters above, 4.5×10^5 sources are expected, a potential foreground "fog" of flare stars (Kulkarni & Rau 2006). If these objects are emitting high brightness temperature bursts $<$1% of the time, as many as 4500 flare stars may be observable. Gyrosynchrotron flares from dMe flare stars usually have smaller enhancements, (the largest being factors of tens) so these will be visible out to smaller distances, but may happen more often relatively speaking. Currently neither the distribution of occurrence of coherent bursts at a particular frequency, nor the distribution of incoherent flares, is constrained, lending considerable uncertainties to these expectations. Better constraints on the expected behavior of coherent bursts from dMe flare stars, as well as good positional accuracy of transient radio sources, will be needed to make identifications with flare stars.

Based on the large amplitude incoherent flares, as well as the relatively large amplitude coherent bursts observed on active binary systems, these objects are potentially visible at larger distances than dMe flare stars. Coherent emission from active binary systems appears to be common: from several epochs observed at 1.4 GHz on HR 1099, moderately or highly circularly polarized emission was observed $\sim$33% of the time (Osten et al. 2004). Enhancements in gyrosynchrotron flares of more than 100 times the quiescent levels at cm wavelengths and shorter have been observed, with recurrence times of several per year. X-ray observations of active binaries reveal that they undergo large X-ray flares about 1/3 of the time they are observed; similar statistics are not available for gyrosynchrotron flares. There are 206 active binaries catalogued within $\sim$200 pc (Strassmeier et al. 1993); Drake et al. (1989) detected 66/122 at 5 GHz. Using the same metric as above, for n=4–8$\times10^{-5}$ active binaries per pc^3 (Favata et al. 1995), f_R=0.54, Jy-level flares detected with sub-mJy sensitivity will be detectable at distances up to $\sim$150 pc, leading to $\approx$300–600 sources. Similar conditions apply here as in transient dMe flare star radio emission to identify transient radio sources as an active binary system.

6. Conclusions

Targeted observations of nearby active stars suggest good chances for stellar detections with

the next generation wide-field radio surveys. Positional accuracy is needed; with variability, the timescale, inferred luminosities, and parameters of the transient radio emission can help identify stellar transients. Targeted observations are still the best way to make progress in understanding the details of flare dynamics. Large area surveys have the best potential to reveal large enhancement and/or serendipitous stellar flares due to long effective on-source times, and reveal whether the behavior seen in targeted observations is typical of the larger source population.

References

Aschwanden, M. J. & Benz, A. O. *Electron Densities in Solar Flare Loops, Chromospheric Evaporation Upflows, and Acceleration Sites* 1997, Astrophysical Journal , 480, 825

Bastian, T. S. *Radio emission from flare stars* 1990, Solar Physics , 130, 265

Bastian, T. S. et al. *Dynamic spectra of radio bursts from flare stars* 1990, Astrophysical Journal , 353, 265

Beasley, A. J. & Bastian, T. S. *VLBA Imaging of UX Ari* 1998, in Astronomical Society of the Pacific Conference Series, Vol. 144, IAU Colloq. 164: Radio Emission from Galactic and Extragalactic Compact Sources, ed. J. A. Zensus, G. B. Taylor, & J. M. Wrobel, 321

Benz, A. O. & Güdel, M. *X-ray/microwave ratio of flares and coronae* 1994, Astronomy & Astrophysics , 285, 621

Bingham, R., Cairns, R. A., & Kellett, B. J. *Coherent cyclotron maser radiation from UV Ceti* 2001, Astronomy & Astrophysics , 370, 1000

Chiuderi Drago, F. & Franciosini, E. *Flaring and quiescent radio emission of UX ARIETIS - A time-dependent model* 1993, Astrophysical Journal , 410, 301

Drake, S. A., Simon, T., & Linsky, J. L. *A survey of the radio continuum emission of RS Canum Venaticorum and related active binary systems* 1989, Astrophysical Journal Supplement, 71, 905

Dulk, G. A. *Radio emission from the sun and stars* 1985, Annual Reviews of Astronomy and Astrophysics, 23, 169

Favata, F., Micela, G., & Sciortino, S. *The space density of active binaries from X-ray surveys.* 1995, Astronomy & Astrophysics , 298, 482

Franciosini, E. & Chiuderi Drago, F. *Radio and X-ray emission in stellar magnetic loops.*1995, Astronomy & Astrophysics , 297, 535

Franciosini, E., Pallavicini, R., & Tagliaferri, G. *BeppoSAX observation of a large long-duration X-ray flare from UX Arietis* 2001, Astronomy & Astrophysics , 375, 196

Güdel, M. *Stellar Radio Astronomy: Probing Stellar Atmospheres from Protostars to Giants* 2002, Annual Reviews of Astronomy and Astrophysics, 40, 217

—. *X-ray astronomy of stellar coronae* 2004, Astronomy and Astrophysics Review, 12, 71

Güdel, M. et al. *Broadband spectral observation of a dMe star radio flare* 1989, Astronomy & Astrophysics , 220, L5

Güdel, M., et al. *The Neupert Effect in Active Stellar Coronae: Chromospheric Evaporation and Coronal Heating in the dMe Flare Star Binary UV Ceti* 1996, Astrophysical Journal , 471, 1002

Hallinan, G., et al. *Periodic Bursts of Coherent Radio Emission from an Ultracool Dwarf* 2007, Astrophysical Journal Letters, 663, L25

Helfand, D. J. et al. *The FIRST Unbiased Survey for Radio Stars* 1999, Astronomical Journal, 117, 1568

Kellermann, K. I. & Pauliny-Toth, I. I. K. *The Spectra of Opaque Radio Sources* 1969, Astrophysical Journal Letters, 155, L71+

Kellett, B. J. et al. *CU Virginis - The First Stellar Pulsar* 2007, `astro-ph/0701214`

Kulkarni, S. R. & Rau, A. *The Nature of the Deep Lens Survey Fast Transients* 2006, Astrophysical Journal Letters, 644, L63

Kundu, M. R. & Shevgaonkar, R. K. *Detection of the dMe flare star YZ Canis Minoris simultaneously at 20 and 90 centimeter wavelengths* 1988, Astrophysical Journal , 334, 1001

Kundu, M. R., White, S. M., Jackson, P. D., & Pallavicini, R. *Co-ordinated VLA and EXOSAT observations of the flare stars UV Ceti, EQ Pegasi, YZ Canis Minoris, and AD Leonis* 1988, Astronomy & Astrophysics , 195, 159

Lee, J. & Gary, D. E. *Solar Microwave Bursts and Injection Pitch-Angle Distribution of Flare Electrons* 2000, Astrophysical Journal , 543, 457

Lovell, B. *Radio Emission from Flare Stars* 1963, Nature , 198, 228

Osten, R. A. & Bastian, T. S. *Wide-Band Spectroscopy of Two Radio Bursts on AD Leonis* 2006, Astrophysical Journal , 637, 1016

— *Ultra high time Resolution Observations of Radio Bursts on AD Leonis* 2007, Astrophysical Journal , accepted

Osten, R. A. et al. *A Multiwavelength Perspective of Flares on HR 1099: 4 Years of Coordinated Campaigns* 2004, Astrophysical Journal Supplement, 153, 317

Osten, R. A., et al.*From Radio to X-Ray: Flares on the dMe Flare Star EV Lacertae* 2005, Astrophysical Journal , 621, 398

Osten, R. A., et al. *Nonthermal Hard X-ray Emission and Iron Kα Emission from a Superflare on II Pegasi* 2007, Astrophysical Journal , 654, 1052

Reid, I. N., Cruz, K. L., & Allen, P. R. *Meeting the Cool Neighbors. XI. Beyond the NLTT Catalog* 2007, Astronomical Journal, 133, 2825

Richards, M. T., *Statistical Analysis of 5 Year Continuous Radio Flare Data from β Persei, V711 Tauri, δ Librae and UX Arietis* 2003, Astrophysical Journal Supplement, 147, 337

Smith, K., Güdel, M., & Audard, M. *Flares observed with XMM-Newton and the VLA* 2005, Astronomy & Astrophysics , 436, 241

Strassmeier, K. G., et al. *A catalog of chromospherically active binary stars (second edition)* 1993, Astronomy & Astrophysics Supplement, 100, 173

White, S. M. & Franciosini, E. *Circular polarization in the radio emission of RS canum venaticorum binaries* 1995, Astrophysical Journal , 444, 342

White, S. M., Jackson, P. D., & Kundu, M. R. *A VLA survey of nearby flare stars* 1989, Astrophysical Journal Supplement, 71, 895

Wild, J. P., Sheridan, K. V., & Neylan, A. A. *An Investigation of the Speed of the Solar Disturbances responsible for Type III Radio Bursts* 1959, Australian Journal of Physics, 12, 369